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During October and November, 1985, continuous streamflow data was collected at five gaging stations on the Colorado River in the reach between Glen Canyon Dam and Lake Mead. These data were used to calibrate the hydrologic computer model, SSARR (Streamflow Synthesis and Reservoir Regulation), which has as one of its features, the ability to route unsteady flow hydrographs. The model was calibrated by trial-and-error until computed flows at the five gaging stations most nearly duplicated recorded flows. After calibration, the SSARR model was used to estimate hourly flows at five gaging stations for the period 1983 through 1986, using hourly flow releases from Glen Canyon Dam as input. An interpolation technique is described for estimating flows at any other point on the river. Due to limitations of this particular flow model, certain biases are built into the flow predictions. The user needs to be aware of these biases before rigorous use is made of the modeled results.

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Abstract

During October and November, 1985, continuous streamflow data was collected at five gauging stations on the Colorado River in the reach between Glen Canyon Dam and Lake Mead. These data were used to calibrate the hydrologic computer model, SSARR (Streamflow Synthesis and Reservoir Regulation) which has, as one of it's features, the ability to route unsteady flow hydrographs.

The model was calibrated by trial-and-error until computed flows at the five gauging stations most nearly duplicated recorded flows. After calibration, the model was used to estimate hourly flows at the five gauging station sites for the period 1983 through 1986, using the hourly flow releases from Glen Canyon Dam as input. This information was used by researchers in the field collecting data for other studies. The model was also use to predict flows at the five gauging station sites based on the various future release scenarios assumed for Glen Canyon Dam. An interpolation technique is described for estimating flows at any other point on the river.

Due to limitations of this particular flow model, certain biases are built into the flow predictions, and the user needs to be aware of these before rigorous use is made of the results.

SSARR was chosen over other unsteady flow models because in the initial phases of the Glen Canyon Environmental Studies, hydrologic and physical measurements of the stream channel were very limited, and SSARR offered an attractive opportunity to develop an unsteady flow routing model with a limited set of data. Now, however, there are over 700 measured and interpolated cross-sections available which should make possible the development of a more rigorously defensible unsteady flow routing model in the future.

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UNSTEADY FLOW MODELING OF THE RELEASES FROM GLEN CANYON DAM AT SELECTED LOCATIONS IN GRAND CANYON

INTRODUCTION

This paper presents a discussion of the development of an unsteady flow routing model for the Colorado River below Glen Canyon Dam at five locations in Grand Canyon National Park, Arizona.

OBJECTIVES

During regimes of average or near average inflow to Lake Powell, the powerplant at Glen Canyon Dam is operated on a demand-load basis. This results in a pattern of high (about 31,000 ft^3/s) releases in the afternoon and low (about 3,000 ft^3/s) in the early morning. As these flows proceed downstream they develop into a diurnal, almost sinusoidal, flow hydrograph. This daily rise and fall of the river is well known to commercial boatmen and others familiar with the river. As these surges of flow proceed downstream, they are modified by the temporary changes in channel storage. The peaks tend to diminish in magnitude, whereas the troughs increase in magnitude. In addition, flows at higher discharge travel faster than lower flows. This also results in a modification of the hydrograph. A typical example of this phenomenon is shown on Figure 1.

Since one of the objectives of the Glen Canyon Environmental Study (GCES) was to evaluate present and potentially different modes of operating the powerplant, it was deemed essential to develop techniques for estimating what the resultant flows would be at various important locations on the river in the Grand Canyon. Knowing this information, other participants of the GCES could determine how the different flow scenarios impacted the beach, recreation, and biologic resources of the canyon. An important secondary need was to provide users with estimates of historical flow at various locations in the canyon at times when they were in the field collecting data.

MODELS AVAILABLE

Modeling unsteady flow has always been a difficult and challenging problem. Even with the availability of high speed computers, most models are difficult to utilize because of the large amount of cross-section data required. DWOPERS, a program developed by the National Weather Service, is data intensive. SSARR, on the other hand, is a flow routing model that can be developed from a limited set of data.

SSARR is an acronym for Streamflow Synthesis and Reservoir Regulation (U.S. Army 1972). It has been in the process of development and application since 1956. It was developed initially to meet the needs of the North Pacific Division of the U.S. Corps of Engineers to provide mathematical hydrologic simulations for system analyses as required for

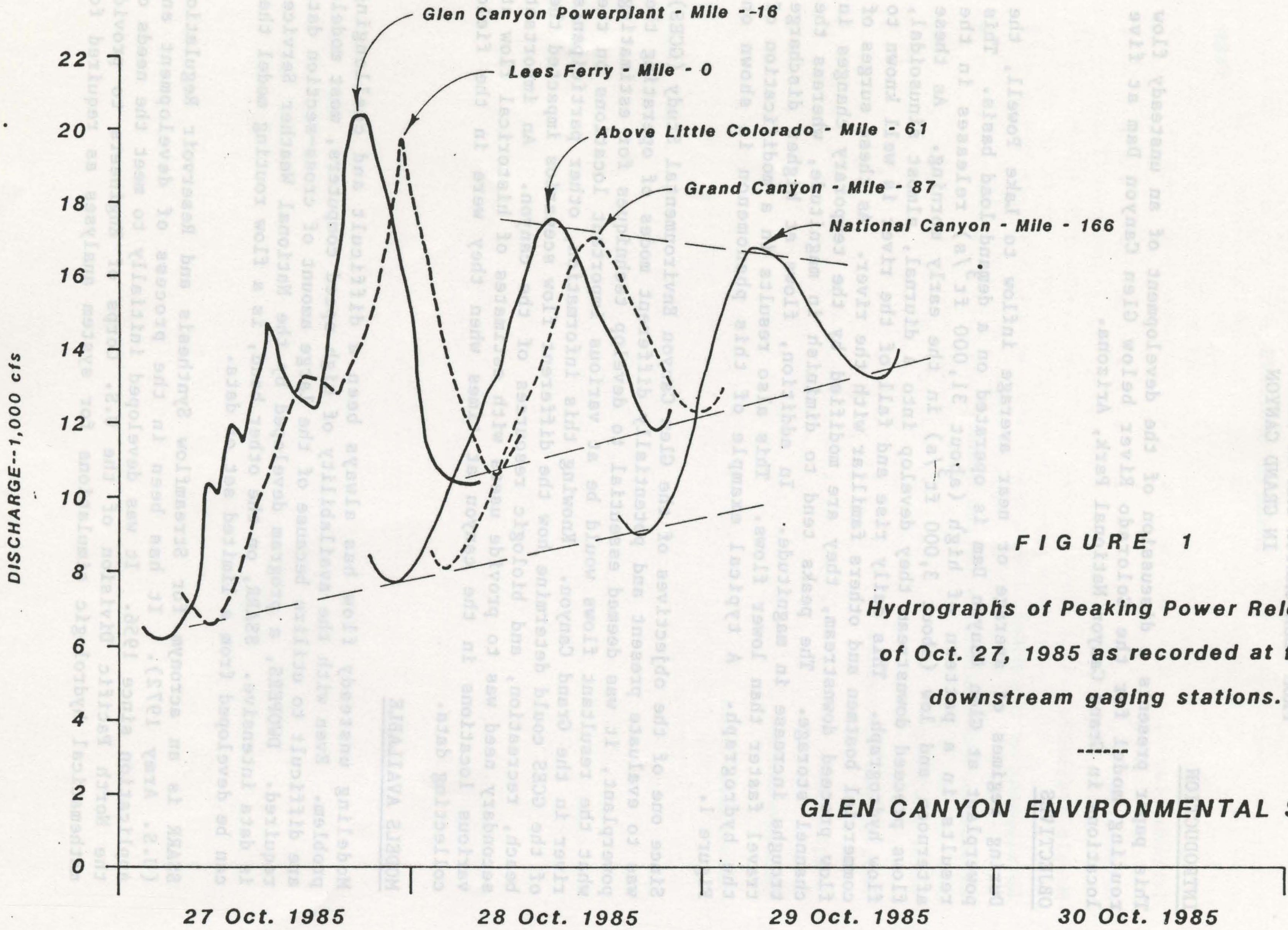

FIGURE 1

Hydrographs of Peaking Power Release of Oct. 27, 1985 as recorded at four downstream gaging stations.

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the planning, design, and operation of water control works. The SSARR model has further been developed for operational river forecasting and river management activities in connection with the cooperative Columbia River Forecasting Unit, sponsored by the National Weather Service, U.S. Corps of Engineers, and Bonneville Power Administration. In recent years, numerous river systems in the United States and abroad have been modeled with the SSARR by various agencies, organizations, and universities.

The successful application of the SSARR model is dependent upon derivations of the various parameters and relationships specific to a particular river system. Streamflow characteristics are primarily determined by trial-and-error solutions with the computer program to obtain the best fit of historic streamflow data. This procedure is repeated until adequate verification of observed flows is obtained and the characteristics tested with independent data.

Routing computations are accomplished by dividing a reach into a specified number of increments of storage which are called routing phases. The time of storage for the channel routing increments is expressed by the following equation:

$$T_s = \frac{KTS}{Q^n}$$

T_s = The time of storage per increment in hours.

KTS = A constant determined by trial and error or estimated from physical measurements of flow and corresponding routing times.

Q = Discharge in cubic feet per second.

n = A coefficient usually between -1 and 1.

The time rate of change of streamflow in a river reach is evaluated by dividing the reach into a series of small increments. Inflow to the uppermost increment is the release from Glen Canyon Powerplant during an increment of time, in this case, one hour. The program then uses a variation of the standard storage routing equation to compute the outflow from the first increment. This flow value becomes the inflow to the next increment of stream and the computations proceed downstream in this manner until the lowermost increment is reached after which the computations begin for the second hour. Basically what it comes down to in calibrating the model, is to vary three parameters (number of routing phases, time of storage per increment, and a dimensionless coefficient) until the computed flows agree as close as possible with the recorded flows.

DEVELOPMENT OF THE MODEL

During the winter of 1985-86, the USGS operated five data collection stations between Glen Canyon Dam and Lake Mead. Data pods or continuous recorders were established or were already in place at each site. Standard streamflow measurements were made during the data collection period and a rating table was developed at each site that allowed for the conversion of the flow depths to a record of hourly streamflow discharge. The stations and the period of record for each are as follows:

Lees Ferry (mile 0)	Full period (permanent gauge)
Above Little Colorado (mile 61)	1 October 1985 to 11 November 1985
At Grand Canyon (mile 87)	Full period (permanent gauge)
Above National Canyon (mile 166)	2 October 1985 to 19 December 1986
Above Diamond Creek (mile 226)	5 October 1985 to 11 November 1985

The period of record common to each is 5 October 1985 to 11 November 1985.

There is also available, the record of hourly releases from Glen Canyon Dam. During this period, releases were in a diurnal pattern and ranged from 1,100 to 22,000 ft3/s.

The flow model was configured as follows. The uppermost station is Glen Canyon Dam. Hourly recorded releases were inputted here and the model computed corresponding flows at Lees Ferry. The recorded flows at Lees Ferry were inputted and the computer program printed out side by side comparisons of computed and recorded flows in both tabular and graphical format. The operator then changed the value of one of the three coefficients and made another run, comparing results with the previous run to see if the change had improved the reconstitution of the observed flows. After many iterations, a point was reached where improvements were negligible and the operator began calibration of the next downstream station, "Above Little Colorado". The input used for that calibration was the computed flows at Lees Ferry. The process continued down to the "Above Diamond Creek" station after which the model was considered fully calibrated and ready for production runs.

The model has the ability to handle tributary inflows. However, this feature was not used since the magnitude of the flows of the Paria River, the Little Colorado River, and Kanab Creek are generally of much less magnitude than the discharge in the main channel. The following table illustrates this.

Table A

Gauging Station	Period of Record	Average Discharges cfs
Colorado River near Grand Canyon, AZ	1965-82	12,710
Paria River near Lees Ferry, AZ	1923-82	30
Little Colorado River near Cameron, AZ	1947-82	237
Kanab Creek near Fredonia, AZ	1963-80	7

The model preserves the volume of flow as it passes from one station to the next. That is, there are no losing or gaining reaches of river unless the operator inputs such a situation.

The model as it is now configured will compute flows directly only at the stations used in its calibration. Estimates of flow elsewhere will require an interpolation process, to be described later. The coefficient values used in the final production runs are as follows.

Table B

Reach	Routing Phases	n	KTS
Glen Canyon Dam to Lees Ferry	2	0.20	9.00
Lees Ferry to Little Colorado River	25	0.30	9.80
Little Colorado River to Grand Canyon Gauge	7	0.30	9.80
Grand Canyon Gauge to National Canyon	81	0.20	3.70
National Canyon to Diamond Creek	99	0.20	0.82

ADVANTAGES AND LIMITATIONS OF THE MODEL

Advantages:

1. Cross-sections and other surveyed data are not required.

2. The model can be calibrated with observed data collected over fairly short intervals of time provided that it is not applied to a range of flows too far outside those observed.

3. The model is easy to develop.

Disadvantages:

1. The model assumes a constant travel time between stations regardless of flow magnitude. This is probably the most serious disadvantage of applying this model to diurnal flows in the Grand Canyon. It is a well observed and now recorded fact that peak flows travel downstream faster than flows during the trough period.

2. Since the input of one station is the computed output from the next upstream station, errors tend to accumulate as computations proceed downstream.

3. Flows can only be computed directly at the stations used in the original calibrations.

4. The model is only valid during the period for which it is calibrated, ie., as the pools scour and fill in their attempt to reach some sort of long-term equilibrium, the flow routing relationships will probably change.

ERROR ANALYSIS

Table 1 shows an analysis of the errors associated with the model. Study of the table will show that the model as now configured has several biases. It tends to underpredict peak flows by as much as 700 to 1100 ft^3/s on the average. This corresponds to about 0.2 to 0.4 feet of stage. It tends to predict the arrival of a peak discharge about 1 hour later than it should. The troughs tend to be estimated several hundred ft^3/s higher than they should. In terms of stage, this error is on the magnitude of 0.2 to 0.3 feet. It also predicts the arrival of the trough about 1 hour sooner than it should. If the exact magnitude and times of the predicted peaks and troughs are essential to the user of this model, he or she is advised to make these adjustments to the computed data results.

Another way of making a statement on the model's veracity is to say that when a surge of water is released from Glen Canyon Dam and after is has traveled 242 miles downstream and has reached Diamond Creek after 48 hours of travel, the model will, most of the time, incorrectly predict the peak discharge by 0.4 of a foot, give or take 0.2 of a foot, in a flow hydrograph that could be fluctuating by as much as 10 feet. It is suggested that this error should be tolerable for most, if not all, users.

RESULTS AND DISCUSSION

Hourly values of releases from Glen Canyon Dam were obtained for the period July 1983 through September 1986 and run through the model to give estimates of hourly flow at the five downstream stations. It is not practicable to reproduce this data with this report, comprising as it does nearly 170,000 flow values. It is available, however, on a floppy disk. Also, temporarily, it can be accessed from a public file on the Bureau of Reclamation's CYBER system.

Hourly values of releases from Glen Canyon Dam for the various powerplant operation scenarios were inputted and run through the model (except for the base load scenario for which the answers are obvious). These data are also available on disk or temporarily on the CYBER.

As stated previously, the model can only predict flows at the locations from which it was calibrated.

To obtain estimates of hourly flow at other locations on the river it is proposed that a straight line interpolation technique be used as follows. The travel times of peaks and troughs were determined from the computed flows of the October 5 to November 8, 1985, period.

TABLE 1

ERROR ANALYSIS

	Peaks			Troughs		
	Magnitude (ft^3/s)	(ft)	Timing (hours)	Magnitude (ft^3/s)	(ft)	Timing (hours)
Lees Ferry Station (33 events)						
Mean difference 1/	10	0.0	0.1	60	0.0	-0.8
St.Dev. of differences	160	0.1	0.6	240	0.1	0.5
Little Colorado Station (20 events)						
Mean difference	-900	-0.3	1.2	320	0.2	-0.9
St.Dev. of differences	530	0.2	1.0	220	0.1	0.6
Grand Canyon Station (32 events)						
Mean difference	-720	-0.3	1.2	260	0.2	-0.9
St.Dev. of differences	460	0.2	1.0	260	0.2	0.9
National Canyon Station (32 events)						
Mean difference	-720	-0.4	1.1	260	0.3	-0.7
St.Dev. of differences	460	0.2	1.0	260	0.3	1.0
Diamond Creek Station (28 events)						
Mean difference	-1130	-0.4	1.3	820	0.3	-1.1
St.Dev. of differences	500	0.2	1.3	410	0.2	0.6

1/ Negative values indicate that predicted events are smaller in magnitude or occurred earlier in time than the recorded ones.

The results were as follows:

Dam to Lees Ferry	3.0 hours with a st.dev. of 1.3 hours
Lees Ferry to LCR	14.5 hours with a st.dev. of 1.5 hours
LCR to Grand Canyon	3.9 hours with a st.dev. of 0.7 hours
Grand Canyon to National	14.9 hours with a st.dev. of 1.8 hours
National to Diamond	11.3 hours with a st.dev. of 1.0 hours

Assume a user wanted to estimate the flows at House Rock Rapid (Mile 17) at 1:00 p.m. House Rock Rapid lies in the reach between Lees Ferry and Little Colorado River. The distance between Lees Ferry and Little Colorado River is 61 river miles. To determine the estimated flow, multiply the time of travel for Lees Ferry to Little Colorado River (14.5 hours) by the fraction of distance the water travels (mile 17 divided by mile 61) as in the computation below:

$$(14.5)(17/61) = 4.04 \text{ hours}$$

The user goes to a table of computed flows for Lees Ferry and determines the value there at 9 a.m. (1 p.m. minus 4 hours (rounded off from 4.04). Then, the user goes to the table of computed flows at Little Colorado River and determines the value at 11 p.m. (1 p.m. plus 10 hours or rounded from 14.5 - 4.04). The two values are then averaged to get the desired estimate of flow at River Mile 17.

CONCLUSION

The streamflow synthesis and reservoir regulation (SSARR) model was calibrated to allow for the calculation and prediction of discharge and stage levels in the Grand Canyon. The modification of the model centered on the matching of discharge volumes, peak and trough hydrograph timing and magnitude downstream at five gauges located within the Grand Canyon for specific periods of actual streamflow data collection activities.

The data used to initialize the model consisted of actual hourly flow releases from Glen Canyon Dam. The model then computed the volume, timing, and stage of the discharge at the five downstream gauging stations. Calibration of the model was performed by a best-fit process utilizing variations in the routing phases, time of storage per phase, and a dimensionless coefficient. The model has several biases that need to be understood before rigorous use is made of the results:

1. The model underpredicts peak discharge levels by 700 to 1100 cfs.

2. The peak discharge levels are predicted to arrive at the gauging stations on an average of one hour later than actual measurements.

3. The trough discharge levels are predicted to be up to 200 cfs higher than the actual measurements.

4. The trough discharge levels are predicted to arrive one hour earlier than actual measurements.

For a majority of GCES study requirements, these biases should not be a problem. To estimate the hourly flows at study sites other than the five gauging station locations, a straight line interpolation techniques was developed. It requires the knowledge of time of travel, time of discharge releases, actual dam discharge levels, and location of the required study site to the nearest gauging station.

RECOMMENDATIONS

The SSARR flow model was selected for the initial phase of the Glen Canyon Environmental Study because it did not require cross-sectional information, but relied solely on a set of easily obtained time-stage relationships. Since the initial development and use of the model, considerable information about the channel has been obtained. In its 225 mile reach of the Grand Canyon, there are now available 708 cross-sections, 209 of which were measured with sonar and the remainder interpolated from aerial photos and a depth-profile survey.

If the Glen Canyon Environmental Studies continue, it is recommended that a new unsteady flow model be selected and calibrated for use; a model that can (1) utilize the cross-sectional information, (2) account for the changing travel time with changing discharge, and, (3) account for the changing cross-sections that results from the scour and fill of the pools.

LITERATURE CITED

U.S. Army Engineering Division. September 1972 (Revised June 1975). Program Description and User Model for SSARR. U.S. Army, North Pacific, Portland, Oregon. PP. 31-32b.